Front. Environ. Sci. Engin. China 2008, 2(1): 109–115
DOI 10.1007/s11783-008-0021-0

RESEARCH ARTICLE

Experimental study on the control of black smoke pollution from the ceramic kilns based on the mechanism of the surfactant and coagulant

Xiao CUI[1,2], **Caiting LI (✉)**[1], **Fei WANG**[1], **Shanhong LI**[1], **Chenchang XIAO**[1], **Yu PENG**[1], **Yunbo ZHAI**[1]

1 College of Environmental Science and Engineering, Hunan University, Changsha 410082, China
2 Guangdong Electric Power Design Institute, Guangzhou 510600, China

© Higher Education Press and Springer-Verlag 2008

Abstract Aiming at the characteristics of carbon black, a new method of controlling the black smoke from the industrial coal-burning ceramic kilns by wetting was brought forward. The carbon black in the flue of coal-burning ceramic kiln was collected for the experiments, and its physical and chemical properties were studied in detail. In order to change the sedimentation and wettability state of the carbon black, the complex solution of the coagulant and surfactant was applied. After a series of orthogonal experiments, the complex solutions with better effects were chosen. Then, the sedimentation percentage of carbon black treated by the selected complex solutions was measured. The optimized complex solutions included Na_2SO_4 (100 mmol/L), sodium dodecyl benzenesulfonate (SDBS) (1.2 mmol/L) and polyacrylamide (PAM) (40 mg/L). After carbon black was absorbed, the complex solutions were clear and colorless. The complex solutions can be recycled, and the sedimentation percentage of carbon black is 94%.

Keywords ceramic kilns, black flue gas, surfactant, coagulant, wetting

1 Introduction

The ceramic kiln industry is widely spread around in china, and most of the kilns are from small and medium enterprises. The air pollution from industrial fuel-burning or natural gas-burning ceramic kilns is far below that of the coal-burning ceramic kilns. However, considering China's national conditions, requiring clean fuel is unrealistic. China's coal storage is rich and widely distributed. In accordance with China's current energy policy, the majority of the ceramics enterprises have used local coal as the main fuel for a long period [1], and the consumed amount of coal accounts for 2/3 proportion of the fuel consumption of industrial ceramic kilns [2].

The coal-burning ceramic industry is an industry with high energy consumption, high resource consumption, and high pollution [1–3]. It can not only promote economic prosperity but also bring pollution problems, in which the pollution of the atmosphere is particularly serious. During the production process, it creates carbon dioxide, nitrogen oxides, and other harmful substances, in which the black smoke pollution is most serious [4,5].

Black smoke is produced by incomplete combustion of coal whose main ingredient is carbon black. The efficiency of carbon black removal by traditional dust wetting removal technique is very low due to its characteristics. According to this, a detailed study based on the physical-chemical properties of carbon black and a series of orthogonal experiments with the surfactant and coagulant were done. In order to improve the efficiency of the sedimentation of carbon black, the mixture of the coagulant and surfactant was added into the solution for wetting dust removal. After a series of experiments, the complex solutions with a better effect were obtained, and at the same time, the absorption mechanism and the application feasibility were discussed.

2 Physical and chemical characteristics of carbon black

2.1 Sources of carbon black

Black smoke contains gaseous chemicals (SO_2 and NO_x), fly ash, and unburned coal particles; its main ingredient is carbon black which had been produced

---

Translated from *Research of Environmental Sciences*, 2006, 19(4), 80–85 [译自: 环境科学研究]

E-mail: ctli@hnu.cn

by incomplete combustion. The key point of controlling black smoke pollution is to remove the carbon black from the smoke.

The carbon black used in the experiment came from the fuel of the ceramic kiln plant in the city of Liling in Hunan Province. In order to unify the metage and calculation process, we put the carbon black used in the experiment in an air blower torrefaction box for 2 h at 105°C, and then put it in the torrefaction box after cooling.

2.2 Composition of carbon black

The main ingredient of carbon black is carbon, including hydrogen, oxygen, and polyhydrocarbon organic compounds. Analysis of carbon black by carbon and sulfur analyzer showed that carbon black contains 96.2% of C, 2.10% of S, and of 0.8% H. Carbon black is created by the incomplete combustion or pyrolysis of hydrocarbon substance (solid, liquid, and gaseous). Its physical-chemistry characteristics are stable at low temperature (< 560°C). Therefore, the carbon black used in the experiment oven-dried at 105 °C in the air blower torrefaction box did not change in physical and chemical properties.

2.3 Granularity distribution of carbon black

The particle diameter analysis equipment of carbon black used in the experiment was a laser granularity distribution analyzer, and the results of the experiments are shown in Fig. 1.

It can be concluded from Fig. 1 that the below 5 μm particle diameter of the carbon black used in the experiment accounted for 50% of all the particles, and the frequency distribution reached the maximum when the particle diameter was 2 μm. Carbon black particles have high surface free energy, and produce strong agglomeration cluster easily [6] even though the addition of a dispersing agent could never get them completely dispersed. Thus, the measurement of particle size by the analyzer was overestimated compared to the realistic value.

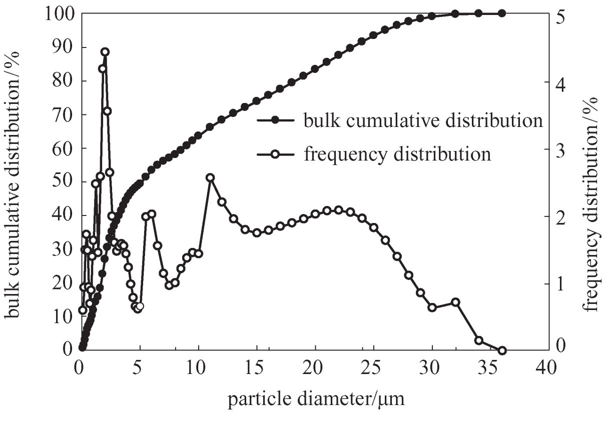


Fig. 1 Granularity cubage distribution curve of carbon black

The electricity microscope scan revealed that the single particle diameter of carbon black was 0.02–1 μm, was very fine and with an almost spherical shape. Since the silica particles tend to accumulate with the black smoke mass concentrations in the ceramic kiln production process (1000–3000 mg/m^3), carbon black monomer in the flue gas flow was vulnerable to be impacted by the collision and was promoted to be accumulated into great granules. Because of the carbon black particle's collision and sedimentation under gravitation, the average particle diameter was slightly larger than the actual average diameter, and the density of carbon black with the smaller particle diameter covered a smaller proportion and subsided in the flue. Therefore, the actual carbon black was a little different to the practical carbon black in the grain diameter, but its chemical characteristics were basically the same.

2.4 Wettability of carbon black

The wettability of dust is indicated by the dust's wetting speed [7]. The wetting rate (V_{20}) is defined by the wetting highness in 20 min (L_{20}). It can be calculated as follows:

$$V_{20} = L_{20}/20. \tag{1}$$

Wetting speed V_{20} indicates a measure of the wettability of dust, and dust can be grouped into four categories (as shown in Table 1)

As a kind of dust powder, carbon black's wettability can be assessed by the wettability index. Carbon black was put in the column glass tube, with an inner diameter of 4 mm and its bottom sealed by a filter paper, and the base of carbon black was kept equal with the water surface. The surface ascending highness of the water was measured after 20 min, and the wetting speed data was obtained by putting the result into the Eq. (1), as shown in Table 2.

Averaging the data of V_{20} in Table 2 obtained the wetting speed: $V_{20} = 2.07$ mm/min. It can be deduced from Table 2 that carbon black is hydrophobic and is difficult to be wetted by water.

Analyzing the physical and chemical properties of carbon black, it can be concluded that, with its small granularity and low density, and with the hydrophobic substance on the surface, carbon black is hardly dispersed in the water. Therefore, the conventional methods of dust removal (centrifugal dust remover, bag filter, and wet dust remover) were not effective.

3 Experimental part

Carbon black is hydrophobic with oily surface, and can not be dissolved in water with rapid absorption or be wiped off quickly in wetting dust-removal industry. It is easy to be taken away from the solution again by the flue

Table 1 Wettability of dust powder

items	kinds of dust powder			
	I	II	III	IV
wettability	utterly abhorhydrophile	abhorhydrophile	middling hydrophile	hydrophile
V_{20}/mm·min^{-1}	< 0.5	0.5–2.5	2.5–8.0	> 8.0

Table 2 Wetting experiment data of carbon black

	examination times				
	1	2	3	4	5
L_{20}/mm	40.8	41.4	42.2	41.2	41.8
V_{20}/mm·min^{-1}	2.04	2.07	2.11	2.06	2.09

gas when breaking away from smoke, causing low carbon black removal efficiency. The experiment set was to enhance the process of carbon black's absorption. Adding the coagulant and surfactant into the absorbing solution of wet dust remover can change the sedimentation and wettability of the carbon black, agglomerate and increase its density, speed up sinking velocity, and shorten the time of sedimentation, and at last, effectively prevent carbon black from rising again.

3.1 Principle of experiment

The experiment was set about to first change the sediment of carbon black, and the coagulant was only added into the absorbing solution to show the sedimentation, wettability and the removal efficiency of carbon black, based on which we could decide whether it was necessary to add the surfactant into the solution or not.

Then, further research on the absorption of carbon black solution, including the wetting and coagulation process, was carried out to study the carbon black removal efficiency. The surfactant was used to improve the wettability of carbon black, and the coagulant was used to change the settlement state of carbon black to select the surfactant mixture with a good wetting effect [8–11]. Inorganic coagulant $AlCl_3·6H_2O$ (PAC) and organic coagulant polyacrylamide (PAM) were added separately, and the inorganic and organic coagulants were added together to select a better sample by comparison and analysis.

The better formula was sorted out by orthogonal comparative analysis. The choice of the best formula was based on two aspects: wetting and coagulation. Wettability was characterized by surface tension (the smaller the surface tension is, the easier the carbon black can be wetted), and the coagulation effect was established by the settlement time and settlement rate.

3.2 Scheme of experiment

The experiment included the steps as follows:

(1) Independent experiment: Adding inorganic coagulant $AlCl_3·6H_2O$ (PAC) to water.

(2) Adding organic coagulant PAM to water.

(3) Adding organic PAM and inorganic coagulant $AlCl_3·6H_2O$ (PAC) to water.

(4) A series of orthogonal experiments with four levels and four factors were done: adding inorganic coagulant $AlCl_3·6H_2O$ (PAC) to the surfactant admixture of sodium dodecyl benzenesulfonate (SDBS)\alcohol polyoxyethylene (9) ether (AEO-9)\(Na_2SO_4).

(5) A series of orthogonal experiments with four levels and four factors were done: adding organic PAM to the surfactant admixture of SDBS\AEO-9\Na_2SO_4.

(6) A series of orthogonal experiments with four levels and four factors were done: adding inorganic coagulant $AlCl_3·6H_2O$ (PAC) and organic coagulants PAM to the surfactant admixture including SDBS, AEO-9, and Na_2SO_4.

According to the experimental formula, a 70-mL solution was taken, and the surface tension was measured by a surface-tension measuring instrument.

The solution with lowest surface tension was selected from the coagulants at different concentrations. 0.5 g carbon black was added in the solution separately, and then the wettability and sedimentation of carbon black were observed and the sedimentation time was recorded after gentle agitation. Finally, the carbon black was filtrated and dried in the oven at 105°C. The carbon black sediment at the bottom of the beaker was quantified to establish the removal efficiency of carbon black.

4 Orthogonal experiment and the outcome of the experiment

In experiment step (5), the best result was obtained. The effect of the experiment was superior to the experiment with the addition of inorganic coagulant $AlCl_3·6H_2O$ (PAC), under the premise of adding the same amount of coagulant, which had lowered the surface tension and raised the removal efficiency of carbon black.

4.1 Orthogonal experiment

The principle and method of each orthogonal experiment was similar. taking experiment step (5) with higher carbon black removal efficiency as an example. A series of orthogonal experiments with four levels and four orthogonal factors were done as follows: adding organic coagulant PAM into the surfactant admixture of anionic surfactant SDBS, nonionic surfactant AEO-9, and inorganic additive Na_2SO_4. The results of this experiment are shown in Tables 3 and 4.

Table 3 Complex parameters of orthogonal experiment

levels	factors			
	Na_2SO_4/ $mmol \cdot L^{-1}$	SDBS/ $mmol \cdot L^{-1}$	AEO-9/ $mmol \cdot L^{-1}$	PAM/ $mg \cdot L^{-1}$
1	0	0	0	0
2	10	0.4	0.03	10
3	50	0.8	0.06	40
4	100	1.2	0.1	100

Table 4 Analysis of orthogonal experiment

items	factors				
	Na_2SO_4/ $mmol \cdot L^{-1}$	SDBS/ $mmol \cdot L^{-1}$	AEO-9/ $mmol \cdot L^{-1}$	PAM/ $mg \cdot L^{-1}$	surface tension/ $mN \cdot m^{-1}$
1	0	0	0	0	78.4
2	0	0.4	0.03	10	40.4
3	0	0.8	0.05	40	40.3
4	0	1.2	0.1	100	40.1
5	10	0	0.03	40	40.2
6	10	0.4	0	100	40.2
7	10	0.8	0.1	0	37.0
8	10	1.2	0.06	10	36.7
9	50	0	0.06	100	37.5
10	50	0.4	0.1	40	35.9
11	50	0.8	0	10	36.9
12	50	1.2	0.03	0	35.0
13	100	0	0.1	10	37.4
14	100	0.4	0.06	0	34.3
15	100	0.8	0.03	100	34.0
16	100	1.2	0	40	34.2
$K1$	199.2	193.5	189.7	184.7	
$K2$	154.1	150.8	149.6	151.4	
$K3$	145.3	148.2	148.8	150.6	
$K4$	139.9	148.4	150.4	151.8	
$k1$	49.80	48.38	47.43	46.18	
$k2$	38.53	37.70	37.40	37.85	
$k3$	36.33	37.05	37.20	37.65	
$k4$	34.98	37.10	37.60	37.95	
R	14.83	11.35	10.23	8.53	

R, which is the maximum subtract value of all parameter average indexes, and can determine the effect of corresponding ingredient in the experiment, was calculated The higher the R is, the more important factor the index is [12]. It can be deduced from Fig. 2 that the effect on surface tension of the four substance sequenced from the greatest to smallest is Na_2SO_4, SDBS, AEO-9, and PAM. Inorganic additive Na_2SO_4 accelerated the association of surfactant SDBS effectively and debased the surface tension, while debasing the surface tension did little effect on nonionic surfactant AEO-9. PAM mostly played the role of flocculation.

4.2 Sedimentation ratio of carbon black

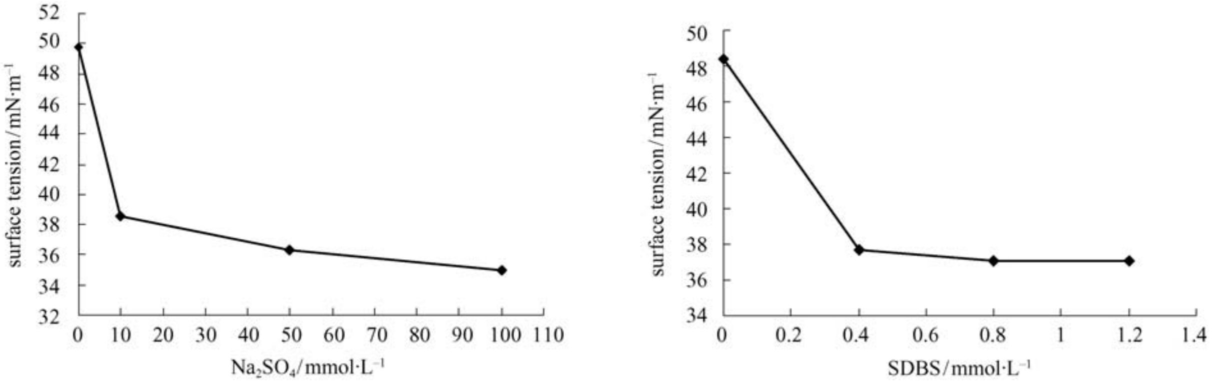
Four groups of PAM solution with the lowest surface tension in four different concentrations were selected, and then 70 mL solution was taken and 0.5 g carbon black was added separately. We observed the sedimentation of carbon black after stirring slightly and recorded the time of sedimentation. Finally, the carbon black was filtrated and dried in the oven at 105°C, and the carbon black sediment at the bottom of the beaker was quantified to determine the removal efficiency of carbon black. The experimental results are shown in Table 5, and the flocculation of carbon black are shown in Fig. 3. (The serial numbers of beaker sequence from left to right are 14, 8, 16, and 15, respectively.)

With the integration of the percentage of sedimented carbon black and the sedimentation time of carbon black, we got the best results: Na_2SO_4 (100 mmol/L) + SDBS (1.2 mmol/L) + PAM (40 mg/L). The sedimentation time of carbon black was around 10 s. During the absorption process of carbon black, the particles of the carbon black agglomerated into a conglobation and sank rapidly. There was only a little accumulation of carbon black on the surface, and most of the carbon black particles were wetted. After the carbon black was absorbed, the complex solutions were clear and colorless and can be recycled. The percentage of sedimented carbon black was 94%.

4.3 Analysis of absorb mechanism

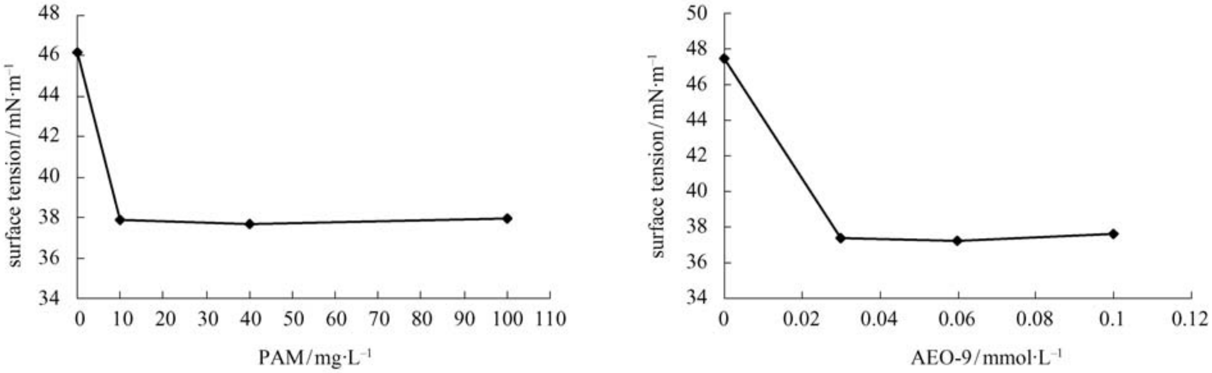
With a hydrophobic surface, carbon black basically can not be spread around the surface of water, but when adding surfactant it can debase the surface tension of water and improve the hydrophilicity, so that the wettability of carbon black can be ameliorated [13]. On microeconomic perspective, wetting is actually the interaction between solid superficial molecules and water molecules [14,15]. The interaction force between solid superficial molecules and water molecules includes not only short range interaction forces, but also long range interaction forces. The surfactant plays the role of increasing the interactional forces and the energy between the surface of carbon black particles and the surface of water molecules, so the wettability of carbon black can be strengthened.

The absorption state of surfactant on the boundary of liquid and solid is connected with the type of surfactant and charge type of solid particles [16]. Carbon black is nonpolar and inclined to absorb negative ion in the water to make it bear a negative charge [17]. Because the Van der Waals force between hydrophobic groups and carbon black particles is strong enough to resist the electricity, excluding power of the same charge, anion surfactant SDBS can partly be absorbed to the negative charge surface of carbon black. Hydrophobic groups of surfactant SDBS can be absorbed on the surface of carbon black particles, and the hydrophilic hydronium groups



(1) effect of different concentration of Na_2SO_4 on surface tension

(2) effect of different concentration of SDBS on surface tension



(3) effect of different concentration of PAM on surface tension

(4) effect of different concentration of AEO-9 on surface tension

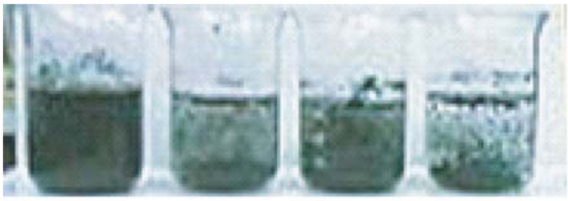
Fig. 2 Effect of different concentrations of Na_2SO_4, SDBS, PAM, and AEO-9 on surface tension

can surround the outside of carbon black particles, so carbon black particles can be extended in the water with hydrophilic hydronium groups outside. At the same time, with the good hydrophilicity of carbon black particles surface, the wettability of carbon black can be well improved. The absorption capacity of anion surfactant SDBS on the surface of carbon black is proportional to the consistence of surfactant SDBS. However, when the concentration of surfactant SDBS is increased, the absolute value of apparent potential energy can also be increased, which can form the electric energy barrier to prevent the formation of the particles. It is more conducive to retain the dispersion and stability of carbon black in the surfactant solution.

Table 5 Sedimentation ratios of carbon black

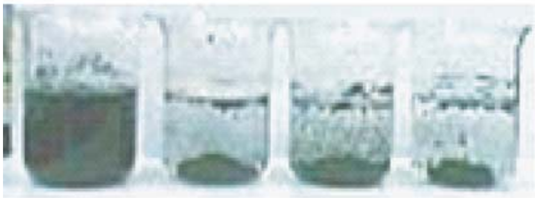
$PAM/mg·L^{-1}$	0	10	40	100
sequence numbers	14	8	16	15
sedimentation time/s	40.5	13.6	12.8	10.7
filter weigh/g	2.1007	2.0871	2.1027	2.1021
carbon black + filter weigh/g	2.4542	2.5388	2.5744	2.4815
carbon black weigh/g	0.3535	0.4517	0.4717	0.3794
percentage of sedimented carbon black/%	70.71	90.34	94.34	75.88

Adding PAC into water can accelerate the agglomerate process and a series of complicated physical and chemical reactions. On one hand, according to the immanent conformation transform discipline of PAC, it will carry through a hydrolyze aggregation reaction, for instance, $Al^{3+} + nH_2O \rightarrow Al(OH)_n^{3-n} + nH^+$ ($n = 1$–6). It can form incalculable aggregation hydroniums in the hydrolyze process, such as $Al_{13}(OH)_{34}^{5+}$, $Al_7(OH)_{17}^{4+}$, $Al_7(OH)_{18}^{3+}$ and $Al_8(OH)_2^{4+}$ [18]. On the other hand, it can cause a series of interface reaction when it encounters the carbon black particles in the water, such as electricity neutralization, absorption, and surface sedimentation chemical action [19]. Under the action of hydraulic turbulent shear force, micro scroll force and other hydromechanical forces, a series of flocculate dynamic reaction will occur. At the same time, particles will collide, and the agglomerate will be felt and lengthened. During the process, with so many physical, hydrodynamic and chemical actions, the external conformation and configuration characteristics of the PAC molecules and carbon black grain diversified continuously: charged particles absorb anti-ion in the solutions to neutralize the exterior charge, so Zata potential dropped, the double-layer distance is compressed shorter, and the double-layer repulsion force between

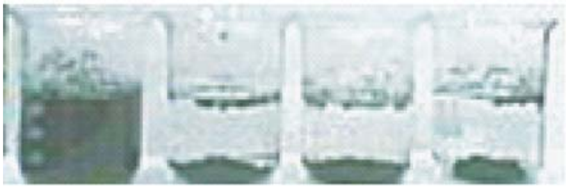


(1) stirring slightly

(2) after 4 s



(3) after 8 s



(4) after 12 s

Fig. 3 Flocculation and wettability impaction of carbon black

particles is decreased. Under the condition of Van der Waals suction domination, the interactions between particles are at the first minimum energy state. At this moment, carbon black agglomerates and separates from the solution. Agglomerate reactions are irreversible and usually occur at the first extreme point in VT-H potential curves. Analyzing experiment (1) and (4), we can conclude in a series of flocculations and dynamics reaction that the volume of carbon black agglomeration is small, and that the carbon black particles suspended in the solutions can not be well delaminated.

Adsorption-bridging action and charge neutralization reaction are recognized as the foundation of macromolecule flocculation action theoretics [20]. Adsorption-bridging action requires polymers with adequate molecule chain. PAM has good aggregation ability, with a long linearity molecule chain in the solution. The length of molecule chain is 100 Å, the width of the chain is 1 Å. The great magnitude of the molecule chain of PAM has a big specific surface area, so it can flocculate well. Every chain of PAM contains thousands of ions and charges. It can neutralize exterior charges, compress the diffusion layer ions and destroy the stability of galvanic layer. All of these make carbon black particles subside. The hydrogen bond of PAM linear molecule chain can also strongly absorb carbon black particles in the suspending solutions. At the same time, carbon black particles can conglutinate together. Polymer molecules that absorbed carbon black particles can be crosslinked with one another to form complex congeries. All of these play a good role in the adsorption-bridging action of carbon black particles. Polarity amide groups of PAM are inclined to be absorbed into the surface of carbon black with the action of a hydrogen bond. At the same time, the long chain of PAM can bridge between the suspended carbon black particles. Carbon black particles can adhere on the chain of macromolecule polymers. When carbon black particles agglomerate big enough, it can subside. The sedimentation of carbon black can be finished in several minutes.

Adding the coagulant separately, carbon black can not be wetted timely. Carbon black particles accumulate on the solution surface. Therefore, the flocculation effect of PAM can not be well embodied.

The complex solutions of Na_2SO_4 (100 mmol/L) + SDBS (1.2 mmol/L) + PAM (40 mg/L) were clear and colorless without the coagulant. No charge neutralization reaction occurred between the coagulant and surfactant, just like in experiment step (6). The cooperation action between the coagulant and surfactant was well embodied. In the complex solutions, Na_2SO_4 could aide the surfactant SDBS to debase the surface tension. So, carbon black could be wetted abundantly and subside rapidly, and the sinking carbon black could agglomerate into a conglobation to subside quickly. After carbon black was absorbed, the carbon black and the solutions had obvious delamination, and the complex solutions were clear and colorless.

5 Conclusions

After a series of orthogonal experiments based on the mechanism of the surfactant and coagulant, the complex solutions, Na_2SO_4 (100 mmol/L) + SDBS (1.2 mmol/L) + PAM (40 mg/L), were chosen to improve the wettability and absorption of the carbon black. At the same time, proper match ratio was screened out. In the complex solutions, the dosage of surfactant was little and the price of chemicals confected in the absorbing solution was cheap, and the solutions can be recycled. When solutions of the surfactant and coagulant were recycled to a certain extent, wastewater will be discharged and treated. So, the quantity of chemicals and water was saved, which could well meet the requirement of circular economy. Carbon black used in the experiment has little difference with the carbon black in reality, so the component of absorption solution can be adjusted when they are used in the industry. The absorption of carbon black is significant to control the black smoke pollution. Wetting dust removal technique with the complex absorbing solutions was selected based on the mechanism of the surfactant and coagulant, and it is possible to absorb carbon black in black smoke efficiently and well improve the removal efficiency of carbon black.

Acknowledgements This work was supported by the Trans-Century Training Program Foundation for the Talent of China (Grant No. NCET-04-0769), the Key Program of the Ministry of Education of China (Grant No.105126) and the Key Program of the Natural Science Foundation of Hunan Province, China (Grant No. 03JJY2002).

References

1. Shen H, Qiang N. The black smoke removal technique of coal-burning kiln. Energy Environmental Protection, 2003, 17(2): 34–40 (in Chinese)
2. Huang L H, Ceng Li K, Ren X T. The prevention and control of NO_x in ceramic kiln. China Ceramic, 2000, 36(6): 23–25 (in Chinese)
3. Shen S B. The elementary discussed measure of powder dust removal in the process of building ceramics factory. Shandong Ceramic, 2000, 23(3): 29–31 (in Chinese)
4. Xiong H, Li W, Shi S X. Research and Development of combined dust collector for coal 2 fired manual operated boile. Industrial Boiler, 2004, 85(3): 43–45 (in Chinese)
5. Oberdorster G, Geliein R M, Ferin J, Weiss B. Association of particulate air pollution and acute mortality: Involvement of ultra fine particle. Inhalation Topical, 1995, 7: 111–124
6. Weth M, Mathias J. The structure of carbon blacks measured with (Ultra) small angle X-ray scattering. Journal of Porous Materials, 2001, 8(4): 319–325
7. Ma G D, Hao J M. The Pollution Control Technique of Atmosphere. Beijing: Higher Education Press, 2001: 136–140 (in Chinese)
8. Xu G X, Ruan F C. Performance Analysis of iron-based and al-based inorganic flocculants. Chongqing Environment Science, 2001, 23(3): 52–55 (in Chinese)
9. Yang J Z, Li H, Ren Q H. The application of complex surfactants in chemical disposal of cobon water. Heilongjiang Pulp and Paper, 2004, (1): 8–9 (in Chinese)
10. Zou L H, Fang Y, Lv S S. Mixing behaviors and application of anionic-cationic surfactants. China Surfactant Detergent and Cosmetics, 2001, 31(5): 37–40 (in Chinese)
11. Angelika B, Roger H, Jurgen O B. Substrate induced coagulation (SIC) of nano-disperse carbon black in non-aqueous media: The dispersibility and stability of carbon black in *N*-methyl-2-pyrrolidinone. Colloids and Surfaces A: Physicochem. Eng., 2005, 253, (2): 155–161
12. Qiu G Y. Profound explanation about analyzing reliability test data by applying statistics. Journal of East China Jiaotong University, 2004, 21(1): 126–129 (in Chinese)
13. Zhao G X. The Physical and Chemical Characteristics of Surfactants. Beijing: Peking University Press, 1984: 421–450 (in Chinese)
14. Zhu B Y, Zhao G Z. The Basic of Interface Chemistry. Beijing: Chemical Industry Press, 1999: 121–221 (in Chinese)
15. Adamson A W. The Physical and Chemical Characteristics of Surfactants. Beijing: Science Press, 1983: 450–478 (in Chinese)
16. Zheng Z M, Obbard J P. Evaluation of an elevated nonionic surfactant critical micelle concentration in a soil/aqueous system. Water Res., 2002, 36: 2667–2672
17. Indrek K, Alex H, Robert H H, Eric M S. Adsorption of surfactants on unburned carbon in fly ash and development of a standardized foam index test. Cement and Concrete Research, 2003, 33: 2091–2099
18. Ge J T. New bipolar electrocoagulation-electroflotation process for the treatment of laundry waster. Separation and Purification Technology, 2004, 36(1): 33–39
19. Huang J H, Zhu C Y, Luo M B. Monte Carlo simulation on surfactant-polymer mixed system. Acta Physico-.Chimica Sinica, 20(7): 690–695 (in Chinese)
20. Xia S Q, Yang D H, Xu B, et al. Chemical and biological flocculation process to treat municipal sewage and analysis of biological function. Journal of Environmental Sciences, 2005, 17(1): 163–167